



ACTS Ka-Band Earth Stations: Technology, Performance, and Lessons Learned

Richard C. Reinhart
Glenn Research Center, Cleveland, Ohio

Steven J. Struharik
COMSAT Laboratories, Clarksburg, Maryland

John J. Diamond
Analex Corporation, Brook Park, Ohio

David Stewart
GTE Technology Organization, Cleveland, Ohio

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David Stewart
GTE Technology Organization, Cleveland, Ohio

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Richard C. Reinhart
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135
richard.c.reinhart@grc.nasa.gov

Steven J. Struharik
COMSAT Laboratories,
Clarksburg, Maryland 20871

John J. Diamond
Analex Corporation
Brook Park, Ohio 44142

David Stewart
GTE Technology Organization
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

Summary

The Advanced Communications Technology Satellite (ACTS) Project invested heavily in prototype Ka-band satellite ground terminals to conduct an experiments program with ACTS. The ACTS experiments program proposed to validate Ka-band satellite and ground-station technology, demonstrate future telecommunication services, demonstrate commercial viability and market acceptability of these new services, evaluate system networking and processing technology, and characterize Ka-band propagation effects, including development of techniques to mitigate signal fading.

This paper will present a summary of the fixed ground terminals developed by the NASA Glenn Research Center and its industry partners, emphasizing the technology and performance of the terminals and the lessons learned throughout their 6-year operation, including the inclined orbit phase-of-operations. An overview of the Ka-band technology and components developed for the ACTS ground stations is presented. Next, the performance of the ground-station technology and its evolution during the ACTS campaign are discussed to illustrate the technical tradeoffs made during the program and highlight technical advances by industry to support the ACTS experiments program and terminal operations. Finally, lessons learned during the development and operation of the user terminals are discussed for consideration of commercial adoption into future Ka-band systems.

The fixed ground stations used for experiments by government, academic, and commercial entities used reflector-based offset-

fed antenna systems with antennas ranging in size from 0.35 to 3.4 m in diameter. Gateway earth stations included two systems referred to as the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS provides tracking, telemetry, and control (TT&C) and Time Division Multiple Access (TDMA) network control functions. The LET supports technology verification and high-data-rate (HDR) experiments.

The ground stations successfully demonstrated many services and applications at Ka band in three different modes-of-operation: circuit-switched TDMA using the satellite onboard processor, satellite-switched TDMA (SS-TDMA) applications using the onboard Microwave Switch Matrix (MSM), and conventional transponder (bent-pipe) operation. Data rates ranged from 4.8 kbps up to 622 Mbps. Experiments included (a) a low rate (4.8 to 100 kbps) remote data acquisition and control using small earth stations, (b) moderate rate (1 to 45 Mbps) experiments with full duplex voice and video conferencing and both full duplex and asymmetric data rate protocol and network evaluation using midsize ground stations, and (c) link characterization experiments and HDR (155 to 622 Mbps) terrestrial and satellite interoperability application experiments conducted by a consortium of experimenters using the large transportable ground stations.

Overview of Ground Stations

The ground stations developed by NASA Glenn Research Center (GRC) and its industry partners included five different

size terminals, each with unique capabilities designed to meet a set of applications for experiments and demonstration at Ka band. The large ground-station facilities of the ACTS/GRC program are the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET). The NGS serves as (a) ACTS primary tracking telemetry and control (TT&C) station, (b) a Baseband Processor (BBP)/Very Small Aperture Terminal (VSAT) Time Division Multiple Access (TDMA) network reference station, (c) two VSAT traffic terminals, and (d) a backup facility to the LET for Microwave Switch Matrix (MSM) experiment operations. The LET serves as (a) a hub for the Ultra Small Aperture Terminal (USAT) star network experiments, (b) a high-data-rate (HDR) terminal in the Gigabit Network, (c) an experimenter station used to conduct technology verification experiments such as wideband dispersion and antenna wetting, (d) an on-orbit testbed for ACTS spacecraft characterization measurements including frequency response and multibeam antenna characterization, and (e) a backup facility for the TT&C function of ACTS.

The family of experimenter or transportable ground stations includes VSAT, USAT, and the HDR terminal. Each terminal was originally designed to support certain applications. As advances in technology occurred over the course of the program, each terminal demonstrated more advanced applications, further demonstrating the capabilities of ground stations at Ka band. The VSAT and ACTS TDMA network were initially used for 1.544-Mbps videoconferencing and teleconferencing based on 64-kbps channels and fade compensation algorithm evaluation. Over the course of the program the terminals were deployed for protocol and network experiments, propagation data collection and analysis, TDMA network availability experiments, and technology experiments to evaluate the satellite multibeam antenna performance. The USAT ground stations were originally designed to demonstrate supervisory control and data acquisition for remote electric utility stations and used kbps data rates. Advances, primarily in solid-state amplifier technology, enabled the stations to demonstrate >1.544-Mbps videoconferencing, highly asymmetric (1.544/45 Mbps) product

and content distribution applications, and 2-Mbps full mesh TDMA/FDMA Internet Protocol (IP) and asynchronous transfer mode (ATM) network experiments. The HDR station was first deployed to demonstrate interconnectivity of supercomputers to conduct interactive computer modeling at high data rates. Over the duration of the program the stations were redeployed to demonstrate high-rate commercial IP augmentation, optimized file transfer protocol (FTP), and technology verification experiments and characterizations.

ACTS has two modes-of-operation: MSM and BBP. The MSM mode-of-operation functions as a bent-pipe memoryless repeater with frequency translation. A microwave switch at the satellite Intermediate Frequency (IF) connects uplink antennas to appropriate downlink antennas for static point-to-point connections. The MSM may also be programmed using a repeating uplink/downlink connection sequence for an SS-TDMA network for HDR operations. The BBP provides onboard storage and routing of baseband signals for the VSAT TDMA network. Signals from each transmitting VSAT are demodulated by the BBP aboard the satellite and routed to the appropriate receiving station by illuminating the appropriate spot beams over the respective transmitting and receiving stations.¹ The satellite burst time plan dynamically updates based on orderwire requests from stations entering the network or if existing stations change their bandwidth requirement.² Table 1 identifies each ground station, its primary mode-of-operation, and typical link characteristics. The LET, HDR, and USAT terminals operate in the MSM mode, and each uses various modulation schemes. Because the transponders use hard-limiting amplifiers, higher order modulation schemes above QPSK were not used. The NGS and VSAT operate in the BBP mode of ACTS. The modems on both the spacecraft and ground stations employ Serial Minimum Shift Keying (SMSK) modulation.

The ACTS ground-station program enabled the commercial industry to make advancements in the design and performance of traveling wave tube amplifiers (TWTAs), low-noise amplifiers (LNA's), high-rate modems, solid-state power amplifiers (SSPA's), and high-power frequency doublers (HPFD's). In

NAME	MODE	ANTENNA (m)	HPA (Watt)	EIRP (dBW)	G/T (dB/K)	BURST RATES (Mbps)	DATA RATES (Mbps)	MODULATION
NGS	BBP	5.5	200	78	30	U/L: 27.5 or 110 D/L: 110	64 kbps to multiple T1 & T2	SMSK
VSAT	BBP	1.2, 2.4	12	60, 66	16-18	U/L: 27.5 D/L: 110	1.792 (max) at 64 kbps increments	SMSK
USAT	MSM	0.6, 1.2	.25, 1.0, 2.0	35-51	15, 21	Up to 2.5 Msps	U/L: low kbps to 8 Mbps D/L: up to 45 Mbps	BPSK, QPSK, CDMA
HDR	MSM	3.4	120	76	28	Up to 696	311 or 622 Mbps	O-BPSK (OC-3) O-QPSK(OC-12)
LET	MSM	4.7	100	78	27	Up to 696	low kbps to 622 Mbps	BPSK, QPSK, SMSK

Table 1 ACTS Ground Station Summary

addition, although outside the scope of this paper, the development of the onboard processing TDMA network enabled various satellite and ground-station technologies not addressed here. The implementation of commercial terrestrial interfaces laid a foundation for terrestrial and satellite interoperability experiments, commercial protocol research and augmentation, and other technical advancements. The radiofrequency (RF) technologies developed for the ACTS ground terminals, with a few exceptions, were mainly extensions of technologies developed at lower frequency bands. Still, the design challenges were quite real and required significant engineering effort to overcome. The final result was high-quality ground-station equipment that continued to perform well beyond the intended operational life of the system.

Ground-Station Technologies

Transmitter

Development and operation of the 30-GHz Ka-band traveling wave tube amplifiers proved challenging in the early years of ACTS. The NGS and LET were the first to procure 30-GHz TWTA's. The NGS and LET began ground-station integration and testing in the late 1980's and early 1990's. Four 54-W units were initially purchased for use in the NGS, followed by three 60-W units for use in the LET, all from the same vendor. The TWT designs used in the LET and NGS units were similar. The TWT's were linear beam devices with a helix type slow-wave microwave circuit.

These first TWTA's experienced several problems. The first anomaly, a spontaneous shutdown of the TWTA protection circuitry, was reported in 1992.³ Testing revealed random output power spikes (1- to 3-dB RF power fluctuations) present at certain frequencies. Naturally, the random power spikes contributed to loss of data bits and resultant increase in bit error rate (BER). The effect would appear in the 10^{-8} BER range. Strong spikes resulted in the spontaneous shutdown of the TWTA. Test data and analysis provided to the vendor contributed to modifications in TWTA design to minimize the effect of the power spikes. Although TWTA's in general experience RF fluctuations, the low BER experiments conducted in the ACTS program were more susceptible to these types of component characteristics. Other problems that occurred were high helix current shutoff and an inability to power a unit on. Over time the latter problem was attributed to the operational procedure of the TWTA.

The operations procedure at the start of the program was to allow the TWTA to run without RF drive during short periods of inactivity and turn off the TWTA during longer periods of inactivity (e.g., overnight). Regularly turning the unit off and on or leaving the unit turned off for short periods of time tended to create gas in the vacuum envelope of the tube. This resulted in a high helix current causing the helix protection circuitry to

power the unit off or prevent the unit from turning on. It is also believed that this operational practice led to shortened TWTA life. These practices and the technical problems mentioned resulted in regular occurrences of TWTA malfunctions and lengthy repair cycles. The TWTA's were routinely sent to the vendor to repair high-voltage components or to degas the unit. Due to the sporadic shutoffs and operational difficulties, the original TWTA's were never run to end-of-life and were replaced by a next-generation TWT from the same vendor (for LET) and new TWTA's from other vendors for both NGS and LET. The original TWTA's had 7000 to 10 000 hr before removal from service.

The TWTA operations procedure for both LET and NGS was changed such that energized tubes were never permitted to idle for long periods of time without high voltage applied. Also, they were always operated with an applied carrier, either radiated or transmitted into a load. Particular attention was also paid to maintaining proper cooling. This resulted in a very stable operating environment, significantly extending TWTA service life.

The combination of change in operational procedures and improvements made in the second-generation TWTA's used in the LET increased TWTA service life. A new TWTA (from the original vendor) was removed from service with over 20 000 hr of operation. The helix current remained stable and only increased near end-of-life, as expected. The LET TWTA from the second vendor provided 100-W output power using a 120-W tube. Internal components, primarily the output isolator. TWTA also employed a helix-type structure tube and power supply in a single housing. The second vendor's TWTA has been in service at LET for over 22 000 hr as of this writing.

Replacement TWTA's for both the NGS and LET were procured from new and different vendors than the original TWTA's. The NGS tubes are capable of 200-W output power, but internal component losses and biasing result in a saturated power level of 150 W at the amplifier output. The slow-wave structure of the tube is a coupled cavity, that is, the tube does not have an actual helix but rather an interdigital delay line that performs the same function as a helix. The circuit was developed as a better way of realizing the slow-wave structure, given the high power level and the stringent size and accuracy requirements in the millimeter wave range. This design is not as broadband as tubes using actual helices. The NGS TWTA's use a split mount design with separate units for the TWT and power supply.

The design life of the second-generation NGS TWT collectors and electron guns are 20 000 to 30 000 hr. However, original tubes delivered with the new TWTA's lasted only 10 000 to 12 000 hr with one premature failure at 2700 hr. The failures occurred for various reasons including materials used in the tube, mechanical shock, and the precision tolerances required in the tube structure at Ka band. Another factor was the stability of the delay line inside the tube. The attenuation of each section must be stable over the operating temperature

range to avoid problems with gain ripple. As experience was gained with tube operation in the NGS and with other users, the vendor examined tube failures and made improvements in the tube design and materials used. The design changes resulted in similar tube design life and achieved a much longer operating life—closer to 30 000 hr.

The VSAT transmitter used Ku-band TWT's operating at 14.6 GHz combined with an HPFD. The TWT, power supply, and fault circuits were enclosed in the Intermediate Power Amplifier (IPA enclosure). The unit produced 45-dBm output with a -5-dBm input signal. The IPA drives the HPFD to produce the final output frequency of 29.2 GHz at 40.5 dBm. The IPA duty cycle was 25 percent under normal operating conditions in TDMA burst mode. AC power is applied to the unit at all times and monitored on an hour meter. The average life of each IPA is about 26 000 hr or 3 years. The IPA power supplies were typically the first to fail. Repairing the power supply units would extend the TWT life to about 30 000 hr.

With the decision to extend the ACTS program in late 1995, after the initial experiment phase (2 years), most VSAT TWT's and HPFD's were in their third year. Due to the IPA reaching end-of-life and design issues with the HPFD, a tradeoff was evaluated: whether to stay with the IPA and HPFD design or use new 30-GHz SSPA's capable of the required 10- to 12-W output power. The SSPA's were available from a limited supply of vendors. However, the output power specification was difficult to meet and some manufacturers could not guarantee a reliable product. Because the change in technologies would incur substantial cost and increase risk, the project stayed with the IPA/HPFD design and replaced the IPA entirely and redesigned the HPFD's.

The first HPFD's used in operation were not designed to operate with a continuous wave (CW) signal applied. Prior to launch, the project identified the need to characterize and test the HPFD's with a CW signal during operations. A second problem with the original HPFD's was that they operated at high temperatures, and several units failed after only a few months due to diode failures. Each HPFD had four diodes that produced the output power and frequency doubling. The new units produced were designed for CW, operated at lower temperature, and used a different diode biasing design. Other design changes included a new balanced diode assembly and additional heat sinks applied to each individual diode. Reduced VSWR made the diode less susceptible to standing waves and voltage spikes. The entire fleet of VSAT's (19) was upgraded with new HPFD's as the original units continued to fail. Although the new HPFD design was more reliable than the original, the units were still the source of many VSAT failures. Experience and testing with the VSAT's determined that the IPA produced voltage spikes that degraded the HPFD's over time. The IPA/HPFD redesign significantly improved the system availability of the VSAT network. Although the technology used required regular terminal maintenance, the reliability data of both the IPA and HPFD enabled system engineers to

plan repairs and service each station before unexpected failures occurred and reduced troubleshooting time to minimize impact to the experiments program.

The USAT transmitters employed low-power SSPA's. In the early 1990's, cost and availability limited these discrete component amplifiers to 0.25 W. Combined with a single-stage upconverter from 800 MHz to 30 GHz, the resultant package was a small 5- by 3- by 1-in. upconverter/amplifier integrated near the feed of the antenna to minimize loss. As solid-state technology matured, a second version of the block upconverter was produced in 1997. The second generation used 1-W Monolithic Microwave Integrated Circuit (MMIC) amplifiers with a two-stage upconverter (70 MHz to 30 GHz), yet only a small increase in size resulted. The new units measured 5 by 4 by 1 in. as shown in figure 1. In addition, 2-W units were also produced in the same size package by combining two 1-W MMIC chips. Two challenges of these higher power units were achieving good component yield and hand selecting the highest power chips for integration. This resulted in good overall performance and stable operation over temperature with losses of only 1 to 1.5 dB at 80 °C. Solid-state amplifiers in the 4- to 10-W range were also available in the late 1990's, but cost and integration prohibited their use. The goal of the USAT was a modest data rate (>1.544 Mbps) with small packaging, which was achieved with the 1- and 2-W units. As successful as these units were in size, operation, and performance, advances are still needed in device yield and unit production and integration to make these products affordable for the mass market.

The HDR station also employed 30-GHz high-power TWTA's. The units were a split-mount design with a 12-m cable to remotely control and supply power to the TWT. The TWTA was mounted on the boom of the antenna near the feed with the power supply and preamplifier rack mounted inside the HDR equipment trailer. Like the LET TWT, the HDR TWT was designed around a helix-type slow-wave microwave circuit with an output of 100 to 120 W and >1-GHz bandwidth. Unlike other terminals, the HDR TWTA remained powered down for

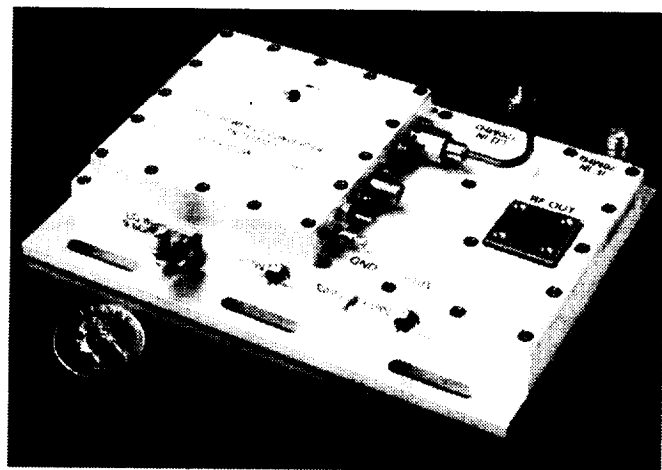


Figure 1 USAT 1-Watt upconverter/amplifier module.

Station	Technology	Initial Issues	Advancements / Lessons Learned
NGS	54 Watt Single Chassis	<ul style="list-style-type: none"> - Sporadic shutdowns - RF power transients - Low reliability 	<ul style="list-style-type: none"> - Improved gun insulation and insulation application procedure.
	150 Watt TWTA-split mount	<ul style="list-style-type: none"> - TWT failure at 10,000-12,000 hours - Cooling fans 	<ul style="list-style-type: none"> - Modified tube design and operational changes led to >30,000-hour tube life with minimal service.
VSAT	12 Watt Ku-Band TWT, HPFD	<ul style="list-style-type: none"> - HPFD reliability 	<ul style="list-style-type: none"> - New HPFD diode and heat sink design - Technology gaps remain for affordable Ka-band 10-12 Watt SSPA.
USAT	.25-2 Watt Solid State/MMIC	<ul style="list-style-type: none"> - Solid state and MMIC cost and availability 	<ul style="list-style-type: none"> - Single integrated block upconverter/amplifier - Advancements in MMIC made devices more available. - Reduction in cost & integration required enabling consumer terminals.
HDR	120 Watt TWTA-split mount	<ul style="list-style-type: none"> - Low reliability - Environmental effects 	<ul style="list-style-type: none"> - Identified potential high voltage interface issues of outdoor installed split mount TWTAs. - Environmental concerns remain for precision tolerances required for Ka-band TWTA operation.
LET	60 Watt TWTA Single Chassis	<ul style="list-style-type: none"> - Sporadic shutdowns - RF power transients - Low reliability 	<ul style="list-style-type: none"> - Improved gun insulation and insulation application procedure.
	100 Watt TWTA Single Chassis	<ul style="list-style-type: none"> - None 	<ul style="list-style-type: none"> - Operational changes led to >22,000-hour tube life with minimal service.

Table 2 Transmitter Technology Summary

the majority of the time, as recommended by the TWTA vendor (different from NGS and LET), despite the experience gained in the NGS and LET operations. TWTA operations without high voltage applied were limited to only a few minutes.

The TWTA used in the beginning of the project had an extremely high failure rate. The high failure rate was attributed to the following: (a) water penetrating the outdoor high-voltage connectors and shorting out the power supply; (b) high-voltage shorting out to chassis due to faulty potting; and (c) temperature fluctuations causing the TWT to defocus. In addition to the failure rates, turnaround time on defective units was excessive. In mid-1997, a different vendor was selected to provide TWTA for the HDR project. TWTA performance and reliability improved.

Table 2 summarizes the transmitter technology used in each ground station. A number of different approaches were taken with each station because of experiment and application requirements. Design changes in TWTA material and integration, changes to TWTA operation procedures, and advancements by industry in solid-state and MMIC amplifiers were highlights of this technology area.

Receiver

Receiver technology experienced modest advancements during the ACTS program. The majority of LNA and low-noise converters (LNC's) were built to specifications often at or

slightly in advance of state-of-the-art at the time. Most of the devices used, with the exception of the VSAT LNC, were technically good devices lasting for many years of service.

The NGS LNA employed quarter-micron HEMT FET, which were the state-of-the-art in the late 1980's when the station was built. Two sets of LNA are used: one at 20 GHz for the TDMA downlink and telemetry beacons and one at 27.5 GHz for the transmit band propagation beacon.

The 20-GHz LNA subassemblies are implemented in a cascade of two stages, each with a gain of 30 dB and a noise figure of 3.0 dB. The station employs three such LNA subassemblies in a redundancy configuration of three for two. The total system noise temperature referenced to the antenna output is 570 K. This value includes an antenna temperature of 123 K and an effective system electronics temperature, including waveguide loss, of 447 K.

The 27.5-GHz LNA also employ two stages each with a gain of 20 dB and a noise figure of 4.5 dB. The total system noise temperature, referenced to the antenna output, is 1687 K. This value includes an antenna temperature of 121 K and an effective system electronics temperature, including waveguide loss, of 1566 K.

The NGS LNA have been in nearly continuous operation, either in test facilities or on the air, since 1991. They have proven to be a robust technology. Few failures occurred over their 9 years of operation, most explained by environmental incidents, that is, periods of high ambient temperature due to

facility HVAC failures or inadvertent signal overload, rather than device failure. Periodic maintenance checks indicated little or no degradation in device performance over the period of service.

The original LET 20-GHz receiver/downconverter used a four-stage HEMT LNA followed by an MMIC mixer and amplifier stages to downconvert the signal to an IF of 3 to 4 GHz. There were three such units produced under a proof-of-concept (POC) development effort. The LNA and downconverter had a combined noise figure of approximately 4 to 5.5 dB with a nominal gain of 25 dB. While the POC units exhibited excessive gain slope across the full 1-GHz downlink band, they exhibited only modest gain slope across their operational band (300 MHz) and were quite usable for applications within that bandwidth. Consequently, they were incorporated into the initial station buildup and used for relatively narrow band signal applications as an efficient use of existing hardware and a cost-savings measure early in the program. However, because of their gain slope across the full band, the POC units proved unusable for wideband applications such as on-orbit link and spacecraft characterization experiments of the entire transponder bandwidth, and emerging HDR modem technology requiring larger bandwidths with minimum gain slope. To accommodate these wider bandwidth applications, it was necessary to replace the POC units with receivers tailored for that purpose.

The LET receivers were replaced with commercially available LNA's and an in-house-designed downconverter. The LNA's selected were identical to those used in the HDR stations. The LNA exhibited a noise figure of 3.5 dB and 50 dB of gain with a minimal gain slope across the 1-GHz band. The LNA used in HDR and LET proved reliable over the project. Many have been in service since 1995 with little or no performance degradation. The few failures that did occur were mainly the result of physical damage to the amplifier.

The VSAT stations encountered significant challenges in the receiver design and performance. The VSAT LNC is a three-stage HEMT LNA, RF bandpass filter, mixer, silicon MMIC IF amplifier, voltage regulator, and fault circuit. Developed in the early 1990's, the receivers exhibited a wide range of performance. The receiver gain was specified at 45 dB, and the noise figure was specified at 5 dB. The performance from unit to unit differed significantly. Each unit was hand tuned at the factory as a result of the performance. The total receiver gain (multiple stages) ranged from 40 to 52 dB and the noise figure varied from 3 to 9 dB. These variations required that the downlink of each station be adjusted to ensure like performance and operation compared to other VSAT's. Because the receiver performance varied so much between units, the entire receiver characteristics drastically changed when different receivers were installed due to failure or service. This lengthened the service time at a particular station to allow time to make necessary adjustments to account for differences in the receivers.

The first-generation USAT ground stations that were used combined LNA and single-stage block downconverters from 29 GHz to 70 MHz. Performance, small size, and low cost were the primary goals of the USAT low-noise downconverters (LND). The original LND exhibited a 25- to 28-dB gain with a 4- to 4.5-dB noise figure over a 40-MHz bandwidth.⁴ The units measured 4.25 by 2.25 by 0.4 in. The LND could operate with 40-MHz bandwidth increments from 19.7 to 20.4 GHz by varying the downlink oscillator. The first-generation LND failed after 3 years of operation. Coincidentally, four of five units failed within the same month after varying scenarios of operation. The fifth unit failed a short time later. Each LND had a similar amount of operation time but was often located in different geographical and temperature locations. No particular operational parameter was identified as being the cause of these failures.

Improvements made by industry during the 1990's resulted in improved performance for the second-generation LND. With a similar size package, the new LND's had a 32-dB gain with a 2- to 2.5-dB noise figure over a 50-MHz bandwidth. A total of 15 units were purchased in 1997 with all units exhibiting similar gain and noise figure performance. These units also covered the 19.7- to 20.04-GHz spectrum but had larger receive bandwidths of 50 MHz (compared to 40 MHz). With the improved noise figure, these units raised the available data rate between small ground stations making them more adaptable to a variety of applications.⁵

Antenna

All the antennas used with the transportable experimenter ground stations were offset fed parabolic reflectors. The USAT and VSAT reflectors were actually Ku-band reflectors, which proved adequate for operation at Ka band. However, propagation experiments conducted on the antennas revealed that wet antenna effects of Ku-band antennas operating at Ka band resulted in a greater loss due to the rainwater and the thickness of the Ku-band dielectric. Minimizing the dielectric thickness at Ka band is needed to reduce loss in the presence of water on the reflector.⁶ As much as 2 to 5 dB is lost due to wet antenna and feed radome effects.

The HDR station was the only experimenter station antenna in the ACTS program made up of individual panels. The USAT and VSAT reflectors (0.6, 1.2, and 2.4 m) were all one-piece structures. The 3.4-m HDR antenna was made up of four individual panels. Station performance validated that using this type of sectioned reflector is a viable alternative for Ka-band operation compared to a single piece reflector. Surface tolerance and feed alignment were adequate for operation.

Both the NGS and LET antennas (see fig. 2) employ Cassegrain-type feed systems. The LET antenna uses the more conventional configuration in which the feedhorn extends from the apex of a 4.7-m dish and couples the reflector optics to

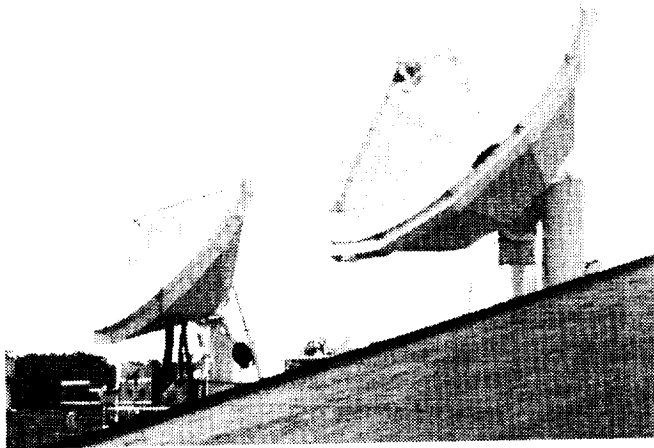


Figure 2 LET (left) and NGS (right) antennas.

transmit and receive equipment located in a hub assembly immediately behind the reflector. The NGS employs a beam waveguide system that couples an aperture at the apex of a 5.5-m dish to a feedhorn located at the base of the antenna. The feedhorn then connects to transmit and receive equipment located indoors in a room directly beneath the antenna.

The NGS feed network follows the feedhorn and consists of a half-wave polarizer and orthogonal mode transducer (OMT) connected by rotary joints. This network allows the antenna to receive and transmit in dual orthogonal linear polarizations with two 20-GHz receive ports and two 30-GHz transmit ports. The 27.505-GHz transmit band satellite beacon is also received at one transmit port and is separated from the transmit signal at that port by a multiplexer and filter assembly. The antenna polarization angle is adjustable through 360° by rotating the polarizer to match the antenna polarization to that of the satellite signals.

The LET antenna feed network is a combined corrugated horn and OMT assembly. Waveguides for both transmit and receive extend into the antenna hub. The assembly mounting plate has four slots along its radius, corresponding to bolts on the antenna structure, to allow polarization adjustments upon installation. Polarization is adjusted by physically rotating the combined feed assembly until peak signal is reached. Polarization adjustment of LET is an iterative process because of the rigid waveguide connections inside the hub. Flexible and rotary joint waveguide would ease the procedure, but it remains a physically challenging task.

Early in system operations a correlation was noted between a decrease in signal level and operation of the NGS antenna deicing system.⁷ At the time it was thought that the observed effect could be a combination of antenna wetness from melting snow and thermal distortion of the antenna reflector. Further investigation confirmed both theories. Antenna wetting effects at Ka band have been investigated by several people and have been quantified as an additional source of link degradation.⁸ Also, subsequent maintenance of the NGS antenna revealed

that the deicer heating system did cause thermal distortion of the antenna structure, which reduced antenna gain. Modification of the heating system reduced the effect although it is still observable particularly at high heat settings.

These heating effects will vary with antenna design, but the experiences gained point out the need for careful attention during the design process to all potential sources of mechanical deformation, to maintain the close surface tolerances required of Ka-band antenna reflectors. The potential usefulness of specific design features to mitigate water and icing effects on the antenna structure should be noted, for example, through the use of shields or other devices to reduce water accumulation on particularly sensitive areas of the antenna.

Modems

The combination of ACTS and the extensive ground-station program enabled a number of advances in modem technology and the demonstration of various modem implementations. From custom ground- and onboard-processing TDMA network medium-rate burst modems to SS-TDMA high-rate burst modems to the use of commercial off-the-shelf low-rate continuous wave modems and ground-based TDMA/FDMA network low-rate modems, the ACTS program enabled flexible network architectures and system configurations.

The VSAT and NGS modems supported TDMA/FDMA operation of the spacecraft onboard processor and the associated TDMA network. The spacecraft and ground-station modems were the same design and operated in burst mode at 110 or 27.5 Mbps using SMSK modulation. The VSAT modems were limited to 27.5 Mbps on the uplink. As part of the network fade mitigation design, the modems could also be operated at one-half their normal burst rates, 55 or 13.75 Mbps, with 1/2 rate Forward Error Correction (FEC) coding, to achieve a 10-dB increase in system uplink and downlink margins.

The NGS and VSAT modem design proved to be stable and well executed, and modem performance was generally excellent over the course of the program. Maintenance problems were infrequent and usually involved power supplies, oscillators, or cooling fans, which are normal failures associated with age and facility environmental upsets. Minor wiring problems also occurred because the units were custom-built. Only one design idiosyncrasy was noted—sensitivity to certain data patterns, for example, long strings of 1's or 0's. This was present in both the spacecraft and ground modems, and was obviated by locking out certain data combinations.

Because of the burst mode operation and the data rates involved, fault diagnosis was more challenging, particularly in the case of intermittent failures. However, the modems were delivered with special test equipment designed to exercise the three different modem pairs (110-Mbps uplink, 27.5-Mbps uplink, and 110-Mbps downlink). The modem special test equipment proved to be a valuable tool in stand-alone modem

fault diagnosis. However, it was also incorporated into the station test equipment suite so that the modems could be exercised over the station transmit and receive paths to verify overall station performance. Regular BER measurements were performed as part of station periodic maintenance as a check on both the modems and the amplitude and group delay characteristics of the station transmit and receive equipment.

The HDR burst modem is a dual-mode device capable of operating in offset binary phase-shift keying (OBPSK) or offset quadrature phase-shift keying (OQPSK) modulation. The symbol rate of the burst modem is 348 MS/s providing data rates of 311 Mb/s in OBPSK or 622 Mb/s in OQPSK. Of the six modems designed and built for the HDR program, three remained in service and fully functional to the end of the inclined orbit program operating for over 2 years without repair. Although the modems performed soundly, it is believed the addition of adaptive equalizers to the demodulator frontend to compensate for the satellite nonlinear transponder and changes in the system due to aging would have enhanced performance.

The companion to the HDR burst modem was the Digital Terminal (DT). The DT interfaced the high-rate terrestrial Synchronous Optical Network (SONET) interface to the burst modem. The DT also managed/controlled the TDMA network scheduling, the Reed-Solomon FEC encoding/decoding, bit scrambling, and the operator interface. The network processor board of the digital terminal depicted in figure 3 is one of six boards that make up the digital terminal. The DT and HDR burst modems were custom-made equipment and the DT is arguably the most sophisticated component of the HDR station. Due to the complexity of the equipment, its interfaces, and operational issues, a large portion of the problems associated with the HDR stations were attributed to the DT.

The USAT ground stations were designed to support a wide variety of applications. Designed with a 70-MHz IF interface, the station could be used with a variety of commercial modems employing standard 70-MHz interfaces. Configured with a 1-W transmitter and a 0.6-m antenna, the USAT could support

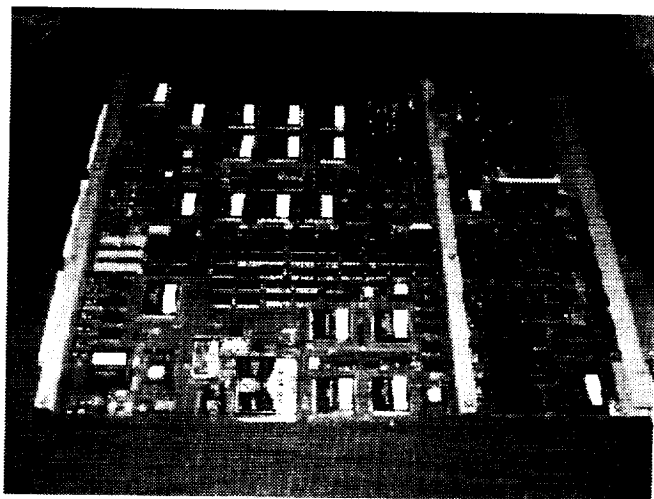


Figure 3 DT network processor board.

2 to 4 Mbps between stations with adequate margin. Configured with a 1.2-m reflector, experiments were conducted using 6 to 8 Mbps. Higher data rates could be achieved by employing Reed-Solomon coding or reducing the available link margin on clear days. The modems allowed the stations to offer a variety of serial and data interfaces such as RS-232, RS-449, DS-1/E1, IP, ATM, Frame Relay, ISDN, DS3, and HiSSi (high-speed serial interface). All the interfaces mentioned were used with the USAT ground stations for testing or experiment applications during the program.

Because the USAT stations used commercial modems and operated in bent-pipe mode, various modulation schemes were used. Most experiments used either QPSK or BPSK; however, CDMA was also used on one occasion. Although the USAT station did not prohibit higher order modulation schemes, the hard limiting amplifiers onboard ACTS degraded the performance of these schemes, and they were therefore not used.⁹ The USAT also demonstrated a ground-based TDMA/FDMA mesh network using commercial products. A four-node full-mesh USAT network was configured and demonstrated. Burst rates of 5 Mbps using QPSK modulation yielded nearly 2 Mbps per node with 1/2 rate Viterbi and Reed-Solomon coding. ATM, IP, and Frame Relay networks operated simultaneously between stations.

The LET also provided modem flexibility. A set of variable rate burst modems from 1 to 220 Mbps operating at 3-GHz IF were built into the station. The modems were part of a POC program in the late 1980's. The modems were similar to the VSAT and NGS modems employing SMSK modulation. A custom digital interface was developed inhouse to handle satellite tracking and timing and included a custom BER test capability. The modems were used to test and characterize the station prior to satellite launch. Shortly after launch a 70 MHz interface was designed for the LET to allow commercial modems used by the USAT stations to operate with LET. The commercial modems handled all satellite-tracking functions, and standard BER test sets were used. The POC SMSK modems were considered for HDR capability prior to the HDR concept in the early 1990's. The drawback of the custom capability was the lack of user interfaces to conduct applications or experiments using the modems. Although the use of the modems was limited to system characterization BER measurements, they still provided valuable data on the performance of the ground station and subsystems and were used to conduct high-rate interference experiments with a companion ground station at GRC with identical modems.¹⁰

Operations

The ACTS program provided the first nonmilitary Ka-band experiment opportunity and experience for the U.S. commercial satellite industry. The objective of operations was to conduct an extensive experiments program to demonstrate Ka-band

operation and services and reduce perceived risk to Ka-band satellite technology and operations. The ground-station fleet was an integral part of the experiments program providing lessons learned in terminal installation and operation. Conducting experiments and operations around the country entailed ensuring system availability and reliability, conducting remote operations, monitoring station performance, anticipating hardware failures, and providing testbed capabilities to verify and maintain station performance.

The VSAT and HDR projects had the most sophisticated remote operations capability of the experimenter terminals. The VSAT relied on dedicated dial-up modem access to each earth station to access station computers to control and configure a host of station and TDMA network parameters and monitor station BER performance. The HDR management network was based on the Simple Network Management Protocol (SNMP) between the HDR network management terminal (NMT, located at the control center) and each digital terminal for the acquisition process, terminal configuration, status, and control. The system included an over-the-satellite-signaling network and backup terrestrial Internet (IP-based) connectivity. The USAT project used dedicated dial-up access to query and control the commercial modem. USAT station parameters were not monitored remotely. All stations used dial-up control for cycling AC power to station hardware.

The VSAT has a data throughput capability of 1.792 Mbps divided among the experimenter and system needs. Primarily, the experimenter used the full 1.544 Mbps or T1 data rate (24 channels of 64 kbps each) for experiment activities allowing four channels for system and station testing, monitoring, and troubleshooting. Of the four channels, the TDMA network computer in the NGS used two 64-kbps channels for uplink and downlink BER testing, and one channel was used for calling into each earth station to poll the BER data from the station. The BER data collected from each station was downloaded to a data base at the network control center. This BER versus Eb/No data was compared to daily weather maps to analyze rain fade events and monitor the status of each earth station. Monitoring and recording the independent uplink and downlink BER of each VSAT station allowed TDMA network system personnel to observe trends in the data indicating possible equipment degradation or failure before it affected the experimenter.

Figures 4 and 5 indicate typical daily BER data obtained from a VSAT station during operations. The plots of each figure starting at the top are (a) Eb/No, (b) uplink BER, and (c) downlink BER. Each parameter is plotted versus time (0 to 24 hr, 18 hr shown). Figure 4 indicates a strong (>15 dB) and a stable Eb/No over 18 hr. The variations in Eb/No represent fade or spacecraft thermal events.¹¹ In the example, there are no rain fade events. The uplink BER depicts bit errors present (jagged line, 10^{-8} in this example). However, the downlink BER indicates an error-free link (solid line). Since the Eb/No is >15 dB, and stable, the station would not expect any uplink fade degradation and should provide an error-free uplink. Thus, the

problem can be remotely diagnosed from the control center as being an uplink problem. Replacing the VSAT IPA resulted in the data illustrated in figure 5 recorded 1 week later. Again, figure 5 illustrates a strong Eb/No, but replacing the IPA now yields an error-free uplink. The information available from the remote capability saved time and cost by reducing the need for engineers and technical support to travel to individual locations for each anomaly or problem. Much of the troubleshooting could be completed from the operations center, which allowed less skilled personnel to simply replace failed subsystem assemblies. Minimum onsite diagnostics were required.

Remote diagnostic capability built into the stations during the program included an additional support computer for station monitoring and control (including FTP and station software configurations) and AGC signal strength and demodulator lock indicators added during the inclined orbit upgrade. The additional upgrade also allowed remote station control and configuration using the TDMA network link. This allowed software upgrades and monitoring without relying on dial-up access. In addition, an external fan alarm was installed to reduce failures due to overheated equipment. Several failures early in the program were attributed to overheated equipment due to failed cooling fans. Other software modifications reduced call setup time between stations and enabled any VSAT to monitor the operation of every VSAT in the network. This capability enabled one person to monitor the network performance and troubleshoot each VSAT from a single field location.

The VSAT employed 1/2 rate FEC coding to increase the system reliability and availability during rain fade events. The coding was enabled when the Eb/No decreased below a predefined threshold. In coded operation, the throughput of both uplink and downlink was reduced by half. Due to the difference in frequency, the fade of the uplink generally determined when coding would be applied to both links. Applying coding to the uplink and downlink paths independently would have improved system efficiency by maintaining the maximum throughput on the individual channels until coding was required. The ACTS propagation and experiments program conducted numerous experiments to characterize the propagation effects at both 20 and 27 GHz independently. The results of these experiments should lead to more efficient systems in the future.

Aside from the TWTA, the HDR station was controlled remotely. The NMT coordinated the HDR acquisition process and data connections through the use of the SNMP. Using the public Internet for station control was an example of the use of commercial technology for NASA missions. However, increasing network security concerns both by NASA (mission/ground station safety) and experimenter sites (corporate firewall integrity) complicated the use of the SNMP. Continued use of Internet technologies for future remote station control will require secure and virtual private network (VPN) technologies.

The HDR network provided long-haul point-to-point and point-to-multipoint full-duplex SONET services at rates up to 622 Mbit/s (SONET OC-12c) with signal quality comparable

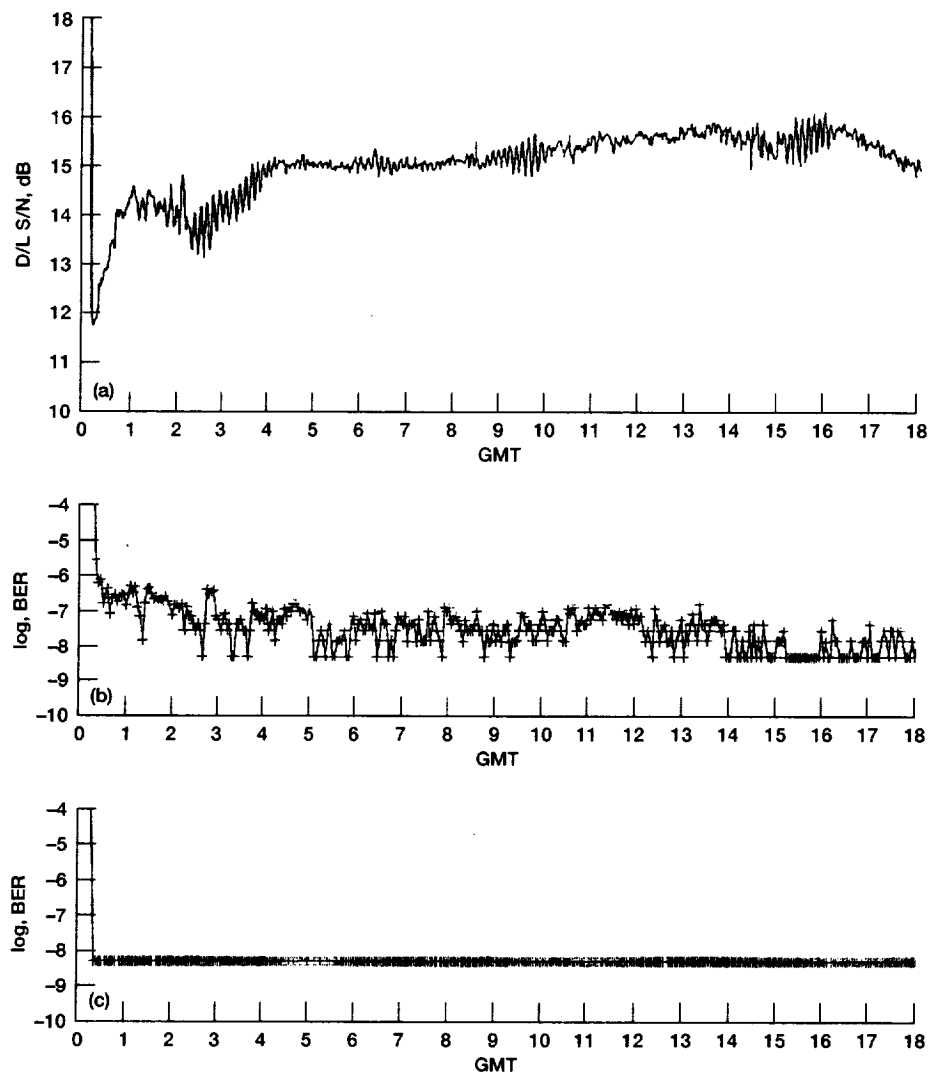


Figure 4 VSAT BER data, U/L BER problem.

to that obtained with terrestrial fiber networks. Data multiplexing over the satellite was accomplished using TDMA techniques coordinated with the switching and beam-hopping facilities provided by ACTS. Transmissions through the satellite are protected with Reed-Solomon encoding providing virtually error-free transmission under modest fade conditions. The user interfaces are compatible with SONET standards performing the function of conventional SONET multiplexers and, as such, can be readily integrated with standard SONET fiber-based terrestrial networks.¹²

Among the most common problems encountered during HDR operations were loss of network connectivity with the NMT and the interface between burst modem and DT. Network service loss was catastrophic since the NMT required

connectivity to all ground stations for network and station acquisition and data link configuration. The burst modem/DT interface was a custom version of the High Performance Parallel Interface (HIPPI). The interface cable had to be reseated before/during experiments to establish good connectivity between the burst modem and DT. Possible items that may have contributed to the problem were lack of cable supports, poor cable design, or impedance difference between the different logic families of the burst modem and the DT. Future designs might consider combining portions of the interface into the modem chassis to reduce the complexity of the interface between systems.

Additions to the HDR system to enhance operations would include having both the standard SS-TDMA mode and

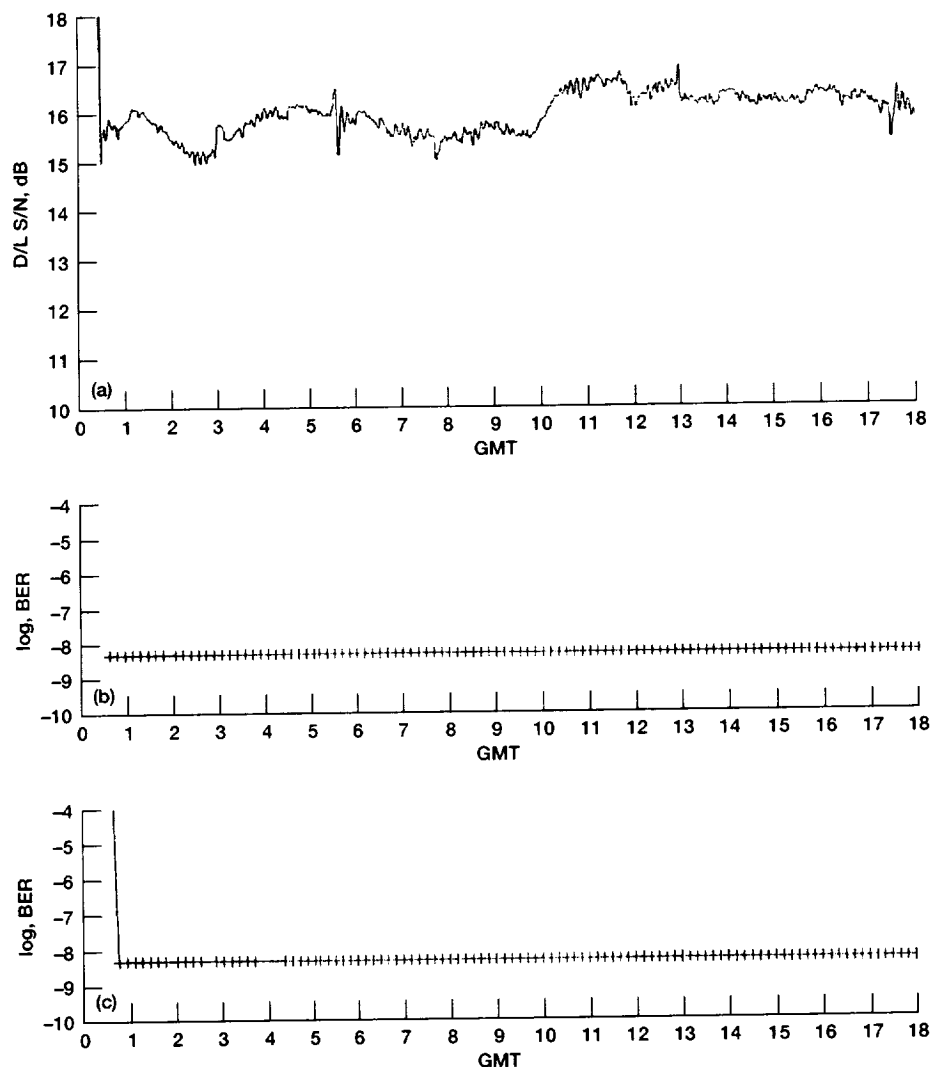


Figure 5 VSAT BER data, error-free operation.

continuous mode (non-TDMA) modem operation and a built-in RF calibration signal for link calibration and testing. The continuous modem operation would have been valuable for station characterization and debugging and provided a more robust link for a point-to-point connection when the TDMA network overhead was unnecessary. Also, an additional dial-up capability to enable PPP (point-to-point protocol) connections from the NMT to each site would have improved system availability in the event of a network failure.

The use of SONET as the HDR terrestrial interface enabled experimenters to use commercially available off-the-shelf OC-3/OC-12 equipment to interface to the HDR station. Further upgrades to the HDR station would include the ability to monitor the status of the SONET connection between the

HDR interface and the experimenter's end-equipment from the NMT operator interface. The operator interface provided numerous statistics on the state of the link including coded and uncoded BER, number of unique words sent and received, number of correctable and uncorrectable errors, but only basic SONET status (i.e., loss of link, loss of pointer, etc.) information. Toward the end of the program, particularly when using the OC-12 data rate, the HDR interface would indicate an error-free link while the SONET equipment reported SONET data errors making the link unusable. Because the system functioned properly early in the program, degradation of the SONET interface or timing issues between the SONET interface and HDR modem electronics are most suspect as the cause of the erroneous statistics. Because of the cost to redesign and repair

the DT late in the program, the systems were used "as is." Often, resetting the SONET interface or rebooting the DT would alleviate the problem.

From a system level, the basic USAT consisted of RF electronics, power supply, antenna and mount, commercial modem, and tracking controller. A support computer allowed remote access to the tracking controller and modem. Due to the simplicity of the stations, the USAT operations were relatively easy compared to the other experimenter stations. The stations were built to minimize cost and most resemble potential future commercial terminals. Test ports and built-in diagnostic equipment were not part of the USAT design. However, the use of commercial modems provided adequate test capability using the built-in CW or BER test capability. Dial-up access to each USAT allowed ACTS network operators to remotely control the modem for test configurations or obtain receive signal characteristics provided by the modem (receive power, BER, AGC, frequency offset, etc). Remotely controlling the USAT modem allowed configuration changes between continuous wave and modulated signals, data rate, and frequency changes. A corresponding modem at the LET allowed full end-to-end link analysis of remote USAT stations.

The USAT ground stations were generally used for experiments on a short duration basis. The intermittent scheduling of each station at varying locations made it difficult to trend station performance for any length of time. Stations were generally bench tested periodically to ensure operation when deployed. Station and system designers must consider the cost and necessity of implementing remote diagnostic capability versus station complexity. For ACTS, the complexity of the VSAT station and TDMA network fully warranted full remote diagnostic capability. It was found to be invaluable for system characterization, monitoring, and analysis in an experimental system. In the case of USAT, the design simplicity allowed the stations to operate without routine monitoring. The limited remote diagnostics provided by the commercial modem proved sufficient for reliable operations.

The NGS and LET are co-located in the same facility at GRC known as the Master Ground Station (MGS). The MGS was staffed on a 24-hr, 7-day basis and was the control center for ACTS Operations. It is linked by terrestrial circuits with the Lockheed Martin ACTS Spacecraft Operations Center (ASOC), which provides spacecraft bus monitoring and control with the NGS providing the TT&C link to the spacecraft itself. A redundant set of ASOC spacecraft monitoring and control equipment is located in the MGS so that the spacecraft can also be controlled entirely from the MGS.

MGS facilities include extensive automation and monitoring capabilities for the NGS/LET stations, as well as for the entire ACTS system, via satellite orderwire circuits and the terrestrial internet. Status and controls are available at the two station operation consoles for station RF and antenna systems, spacecraft TT&C functions, and the ACTS BBP, HDR, and MSM networks, including the spacecraft communications payload.

During most operations, one operator at the MGS and one at the ASOC facility can operate the entire system. In addition to system operations, station operators also perform data-processing tasks for the enormous amounts of data collected daily by the system.

The extensive automation available could have allowed unattended or remote operation. However, in practice it was quickly found that while such automation was useful and good, there is no replacement for a live operator onsite in main control facilities. Protection of the considerable investment in spacecraft and ground system assets, and immediate service of normal and extraordinary system needs including response to system users, are best served with live around-the-clock staffing. While relatively uncommon, there were several significant occasions during the 7-year mission when incidents such as facility roof leaks and air conditioning, power, computer, and communication equipment faults were immediately handled by the on-duty operator, minimizing system outages and containing potentially catastrophic equipment damage. The tradeoff and cost of fully automated and call-in processes must be compared with the value of immediate response times when system availability and fault repair are considered. The ACTS system and equipment, though designed as an experimental system with limited redundancy, experienced excellent availability throughout the entire 7-year mission. This was due in large part to the immediate availability of onsite support. System designers would do well to note this significant lesson learned.

Integration

The integration of each ground station was unique to the technology used and available during its development, cost considerations, and common practice. Each field terminal and gateway earth station had unique integration issues to resolve or manage. Although the design and implementation of each station is beyond the scope of this paper, examples of the challenges or successes of each terminal are highlighted to provide lessons learned for future Ka-band ground station and system designers.

For the VSAT, the major challenge was the integration of the electronics enclosure located at the feed of the antenna. The enclosure contained the LNC, phase locked oscillator (PLO), HPFD, voltage regulator, fault circuits, orthomode transducer, feedhorn assembly, and various waveguide and filter assemblies both at 19 and 29 GHz. Experience with operating and maintaining the station determined that the LNC was positioned too close to the HPFD. As described earlier, the HPFD operated at high temperature, even after redesign. The LNC was installed directly above the HPFD exposing the receiver to excessive heat without adequate air circulation or ventilation. The excessive heat affected the receiver noise figure and gain, decreasing the receiver sensitivity and increasing system noise.

Combined with inconsistent receiver performance, the added heat further complicated operations and adversely affected performance. To improve the design, the HPFD inside the electronics enclosure could have been installed inside the IPA, near the TWT. In that configuration the TWT could be monitored for voltage spikes using protection circuits to protect the HPFD input. This design change would have corrected two problems: (1) heat adversely affecting the LNC and (2) additional circuitry to protect the HPFD from TWT power fluctuations (spikes). Due to implementation cost, the project used the current configuration throughout the program. The link margins built into the systems were sufficient to conduct operations without impact to experiments.

A second problem with the electronics enclosure was the presence of moisture in the feedhorn and in the enclosure itself. The feedhorn moisture was corrected by replacing the "O" ring gaskets, using feedhorns with better window adhesive, and pressure testing the membrane seal. The moisture inside the enclosure was corrected by changing the feedhorns and seals, changing the desiccant packs inside the unit, and replacing the gasket inside the enclosure cover. The moisture inside the enclosure damaged the various electronics inside. The HPFD failed as moisture damaged the diodes. The LNC, PLO, and voltage regulator performance were also affected by moisture. The experience with the VSAT electronics enclosure illustrates the need for careful moisture-proofing design in outdoor electronics and periodic maintenance of small but important details such as feedhorn protective windows, O rings, and gaskets and careful assembly.

A highlight of the NGS integration was extensive IF and RF loopback capability built into the NGS to permit off-the-air performance verification of station transmit and receive paths for both TT&C and TDMA functions. These features were useful for testing and fault isolation, particularly when used with the modem test equipment. Also, since the ACTS BBP is a regenerative repeater, that is, the uplink carrier cannot be observed on the downlink, they enabled link monitoring that otherwise would not have been available. In practice; however, the reliability of station equipment over the mission life was very high, and aside from periodic maintenance checks and a few troubleshooting episodes, the loopback features were rarely used. However, the loopback paths were used extensively for station characterization testing prior to launch.

The inclusion of a spacecraft simulator in the MGS station test equipment proved to be more useful in practice than the built-in loopback paths. The simulator is the engineering model of the ACTS spacecraft communications package and contains a single transponder with a baseband processor and microwave switch matrix. The simulator is functionally equivalent to the flight communications package. It was used as a testbed in the development of the NGS and was then incorporated into the station test equipment suite. Station transmit and receive paths were connected to the simulator at both IF and RF. A VSAT terminal located in the station was also connected to the

simulator to emulate a small TDMA network. The spacecraft simulator allowed the NGS and VSAT to simulate BBP operations as a complete system, all within the station equipment. Most importantly, it allowed network personnel to investigate problems offline, with the spacecraft in use by MSM experimenters, thus, not requiring valuable spacecraft time for troubleshooting.

The integration, assembly, and maintenance of the USAT stations, which consisted of only seven active components, were relatively easy. The first-generation USAT (0.25-W upconverter/amplifier) was configured using two enclosures. The first enclosure held the IF section of both the transmit and receive and the first-stage uplink and reference oscillators. The upconverter/amplifier, LND, and remaining oscillators were installed in a second enclosure. The configuration made for easy access to all components. Heat was dissipated through the base of the aluminum enclosure and did not affect other components. The drawback was the number of cables required to interconnect both enclosures (Tx, Rx, ref LO, power) since with one enclosure mounted at the feed and the second on the mount, the cables had to allow a small degree of movement for station pointing and later inclined orbit satellite tracking.

The second-generation USAT used a slightly larger enclosure (fig. 6) to hold all the active components (2-W upconverter/amplifier (base), LND (sidewall), three oscillators (two on sidewalls, one in middle of enclosure), reference oscillator (back wall) and IF amplifier (sidewall)). A change in the upconverter/amplifier design to include all the uplink electronics in a single package reduced the number of assemblies and interconnects. Also, the components were more tightly integrated into the enclosure. Integrating the components into the package increased the assembly time, but reduced station

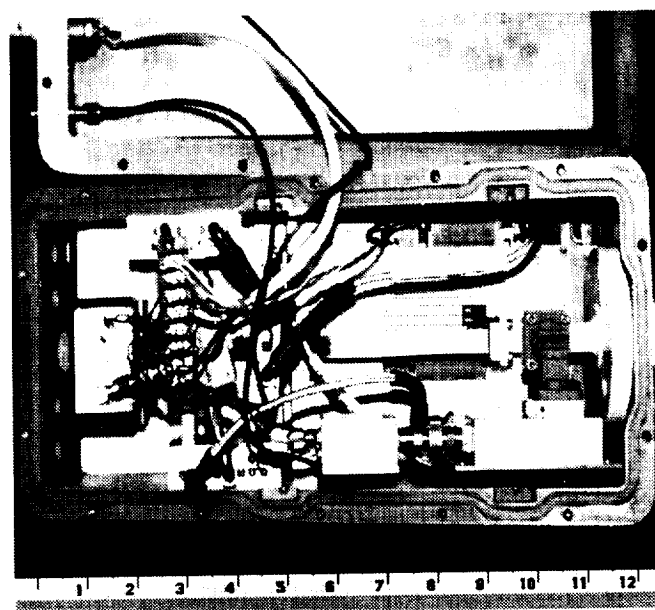


Figure 6 USAT RF enclosure.

installation time and complexity by eliminating one enclosure. In both cases, the DC power supply used by the station was separate from the electronics.

The LET was designed to evaluate the link between ground station and satellite. Numerous test ports were designed into the system such as receive, transmit (both before and after the TWTA), loopback, calibration signal source, and all station oscillators. Built-in test equipment provides power, frequency, and spectrum measurement at each test port. Station modems and built-in BER test system, described earlier, provide a pseudorandom data source for detailed BER characterization. Built-in loopback capability and RF connections to the MSM of the satellite simulator (ACTS transponder engineering model), described earlier, proved valuable for offline system testing, station checkout, and fault isolation. Access to test ports on both uplink and downlink signal characteristics proved invaluable during system anomalies and characterization experiments.

As described earlier, LET station equipment was divided between the antenna hub (directly behind the antenna reflector) and an area directly below the roof under the antenna. The receiver, TWTA, and portions of the upconverter are housed in the hub, with the remaining components and all test equipment located inside. An environmental control system and flexible ductwork from the building to the antenna hub provided an appropriate temperature-controlled environment for hub electronics. The NGS beam waveguide antenna allowed all transmit and receive equipment to be located indoors.

The LET electronics-in-hub configuration is the more economical design, but is inconvenient to maintain when work is required on the hub electronics, particularly in bad weather. A small platform constructed on the back of the antenna structure helped safety and stability, but accessing electronics inside the hub was still difficult. The NGS beam waveguide design with all equipment indoors allows easier and more immediate access for maintenance and adjustments and direct access to antenna input/output flanges for measurements and tests. The design also allows implementation of more complex transmit/receive systems and easier configuration changes. These features are particularly well suited to experimental operations and in-orbit test facilities. The disadvantage is the added expense of the beam waveguide design. Station designers will need to weigh the above factors against complexity required and intended service in cost-benefit analysis of future designs.

Unlike the NGS and LET, the VSAT was not equipped with loopback capabilities either at RF or IF. Lack of any loopback capability made station testing difficult and relied upon the TDMA network to evaluate station performance. Nonstandard IF of 758 MHz (transmit) and 1620 MHz (receive) prohibited loopback testing of the modems. Further, to contain costs, the stations were not equipped with many test points. Test points in both transmit and receive to measure various frequencies and power levels throughout the system would have proved valuable and allowed easier alignment, troubleshooting, and testing of the system.

The HDR stations were developed with TDMA Control Card loopback (circuit card only), modem digital loopback (internal to modem only), and IF loopback (external to modem). However, the stations did not have an RF loopback capability. The loopback functions were extremely useful to debug and test the ground stations to isolate problems to either the digital terminal, the burst modem, or to the RF system. RF loopback capability would have been valuable to characterize individual station performance, but again, cost and implementation must be considered.

The electronics of the HDR station were divided between the equipment trailer and the boom of the antenna. The upconverter and downconverter electronics were installed in the equipment trailer with the LNA and TWTA mounted on the boom of the antenna. As a result, both the transmit and receive paths had approximately 12 m of waveguide between the equipment trailer electronics and the antenna feed electronics. The 750-MHz bandwidth signals of the burst modems transmitted over these long waveguide runs introduced crosstalk between the I and Q channels of the OQPSK signal due to group delay dispersion of the waveguide.¹³ Custom waveguide equalizers with opposite group delay were installed to mitigate the crosstalk and improve station performance.

Inclined Orbit

By deleting the final north-south stationkeeping maneuver of standard ACTS operations, ACTS experiment operations were extended by operating in an inclined orbit. East-west stationkeeping was maintained due to the small amount of fuel required to execute east-west stationkeeping maneuvers. The resulting orbital inclination increased at a rate of about 0.8° per year, which made antenna tracking a requirement for all stations. Because of their aperture size, the LET and NGS antennas already had existing tracking systems, which were used throughout the ACTS program. Both systems operated in a step-tracking mode using the 20-GHz telemetry beacon signal from the satellite. No modifications were made to the NGS-tracking system. However, the LET-tracking system (and antenna) had been developed under a POC contract more than 12 years earlier. As with the LNA, the antenna and its tracker were put into service without modification as a cost-savings measure. Although the tracking system functioned technically well, a new commercial system was installed to assure better system availability (spare parts, current electrical equipment, etc.) throughout the remaining program.

There were several impacts to the ground-station program that resulted from inclined orbit operation. Each field station required new mounts and electronics to track the satellite. Also, the BBP TDMA network and HDR network equipment required software modifications to accommodate the increased range and range rate variation in the inclined orbit. All modifications to the earth stations were performed inhouse to reduce costs and to achieve stringent pointing requirements for all stations.

Because of the increased range and range rate variation in the inclined orbit, there were impacts on the BBP TDMA network acquisition process, which potentially restricted the times at which proper acquisition could occur. Tracking (of timing) was also affected, which late in operations restricted the times that synchronization could be maintained. The changes were gradual; however, and occurred as predicted. Minor software modifications were made to both the VSAT and NGS software to mitigate most of these effects, but complete mitigation would have required additional software modifications to ground equipment. Given the projected length of inclined orbit operation, it was decided to work around the limitations when necessary by modifying operating times and procedures. This approach proved successful. No real limitations were encountered until very late in the program, as expected.

The HDR software system was expected to accommodate the satellite's increase in range rate and Doppler shift, but software modifications were made to the acquisition process (range time determination) algorithm. The initial round trip time (RTT) was estimated based on the ground-station location and ephemeris data, with further RTT updates made once acquisition was complete. After operating in inclined orbit, it was found that the RTT software modifications functioned properly, but the increase in range rate limited the times at which an HDR station could acquire. Station acquisition was limited to the north and south extremes of the satellite's orbit. Once acquired; however, the HDR stations maintained acquisition, even at the range rate peak, through the center of the orbit. Review and analysis of the HDR acquisition process revealed that the most likely cause of the problem was a restriction in the acquisition software. Due to cost and time to correct, the software was not modified. Instead, the operations schedule was adjusted, with no impact to station performance.

A commercial antenna-tracking controller was modified to support remote configuration, control, and monitoring required by the field stations. The majority of system parameters were programmable by dial-up modem or through support computers using the existing station remote control capability. The most significant feature implemented in the controller was the ability to remotely upload and download the 24-hr history and future movement of the antenna system. The ability to access and control this table allowed station personnel to analyze ground-station position relative to satellite position (download feature), program the antenna to move to predicted positions in the case of a new installation (upload feature), or repeat the past position for a specific time of day in the absence of a received signal (memory track). Because of ACTS scheduling, the receive signal used by the VSAT and USAT stations for closed-loop antenna tracking was not always available. The memory track featured allowed the stations to use the last known position for a particular time slot. This feature maintained suitable pointing until the station was again scheduled for experiments at which time the position table in memory would update.

Each field terminal used the tracking controller for inclined orbit operations. The controller required a 0- to 10-Vdc signal input for closed-loop tracking. The memory table provided open-loop tracking in the absence of a downlink signal. This feature was often used due to ACTS scheduling of particular earth stations. Each station addressed the closed-loop signal requirement based on its system architecture and capabilities.

The VSAT used a feedback voltage from the automatic gain control (AGC) card present within the VSAT as input to the tracking controller. Minimal station design was required to utilize the AGC feedback signal for the controller. However, to ensure an accurate AGC feedback signal, the controller was modified to accept a contact closure signal from the VSAT indicating demodulator lock when synchronized with the BBP. The AGC signal was only valid in this mode.

Figure 7 illustrates a tracking signature of a VSAT 1.2-m system compared to the NGS with both co-located at GRC. The figure indicates accurate SAT tracking relative to the NGS reference with a maximum difference of $\leq 0.2^\circ$ in either azimuth or elevation, corresponding to < 1 dB pointing loss.

Although the use of commercial modems gave the USAT flexibility in modulation and data interfaces, the lack of a digital interface posed a challenge for inclined orbit operations. To enable the USAT to track the satellite independently of the modem used with the station, a separate circuit was designed to provide the required analog input signal to the tracking controller. Because the LND filtered the beacon signal from the satellite, the analog signal was derived from the 70-MHz-received signal at the station. A series of narrow bandpass filters and appropriate amplifiers followed by a microwave detector followed by a narrow band digital filter derived the required signal. The detector was operated in the low-sensitivity region such that the voltage variation was approximately linear with input power. Figure 8 illustrates a typical tracking signature of a USAT with a 0.6-m reflector compared to that of the NGS. Both are located at GRC. The plot illustrates the ability of the USAT to follow the NGS pattern from which satellite range and position data is verified. Also evident is the lack of resolution at the satellite location extremes due to the larger beam width of the smaller USAT aperture. Pointing error in the example is approximately 0.2° azimuth and 0.4° elevation, which contribute approximately 1-dB pointing error loss.

Because the tracking signal was derived from the received communications signal, the USAT antenna controllers were configured to conduct their antenna peaking at alternating intervals so that signal variations induced by uplink antenna tracking did not confuse the downlink antenna-tracking process ultimately causing both stations to mispoint.

The USAT-tracking mount was an easily deployable terminal with minimal impact to installation and little or no increase in the overall terminal size once installed. Figures 9 and 10 show the USAT mount before and after inclined orbit modifications, respectively. The fixed mount shown in figure 9 shows

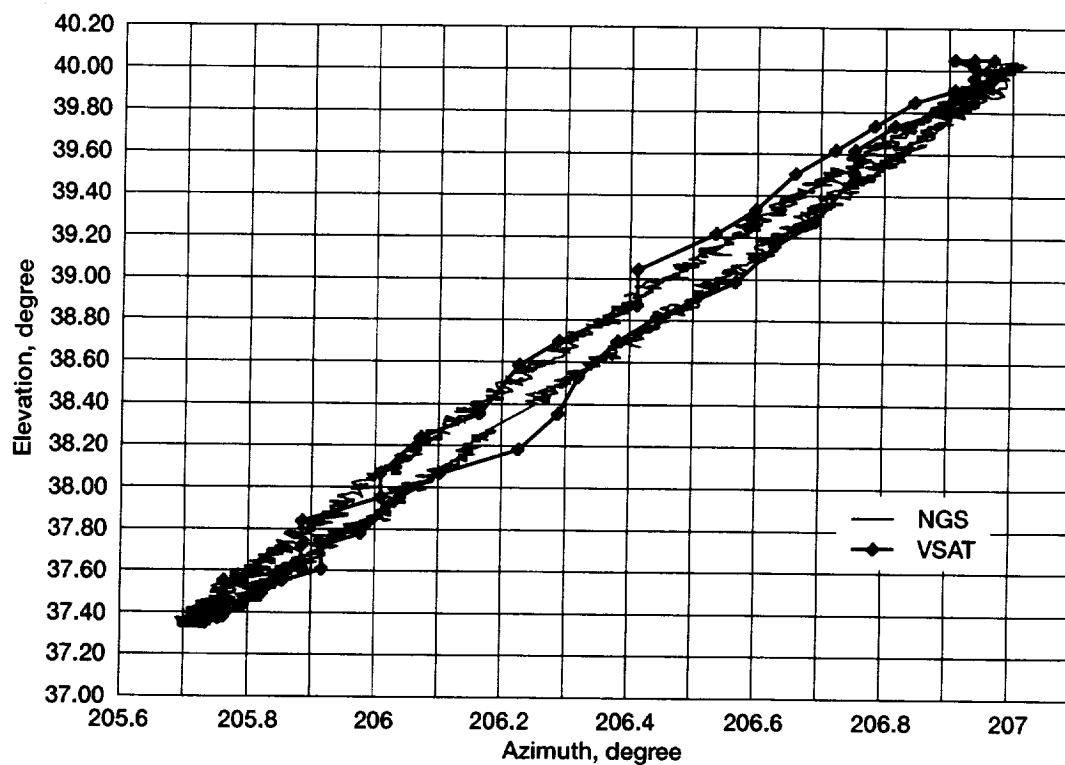


Figure 7 VSAT 1.2-m inclined orbit tracking versus NGS reference.

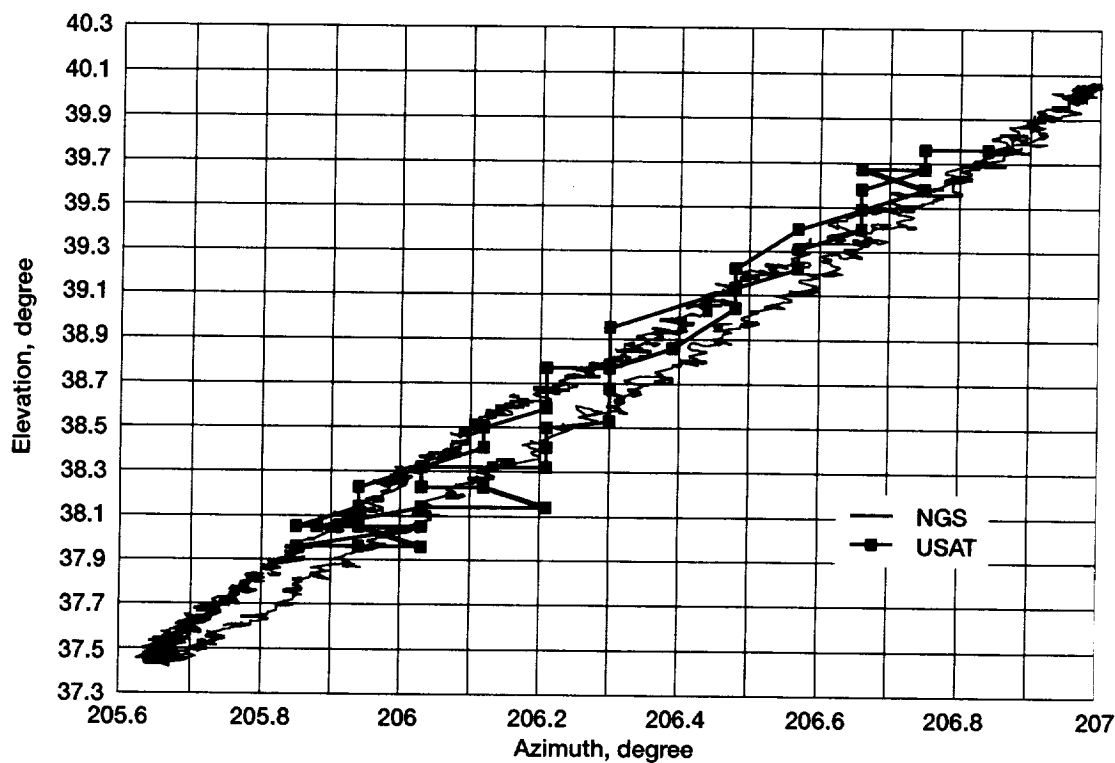


Figure 8 USAT 0.6-m inclined orbit tracking versus NGS reference.

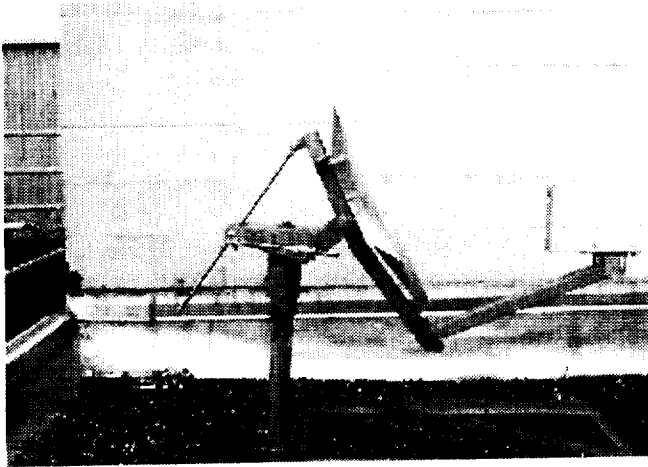


Figure 9 USAT fixed mount.

threaded rods behind the reflector used to adjust azimuth and elevation. The RF electronics are installed in front of the reflector. Figure 10 depicts the inclined orbit-tracking mount. The reflector and RF electronics are configured in the same way as the fixed mount. However, moving the azimuth axis-of-rotation from behind the reflector to between the reflector and electronics improved the stability of the mount. Adjusting the mount center-of-gravity and slightly reducing the mount height reduced the ballast required for installation.

The inclined orbit mount required additional installation time for adjustments and pointing to minimize the coupling of elevation to azimuth movement inherent in the design. The coupling of elevation movement due to azimuth occurred because the azimuth axis-of-rotation was angled relative to the ground compared to traditional mounts. This adjustment enabled the required degree-of-motion given the design constraints. The impact was minimal for the small inclination of ACTS, provided the mount was properly installed.

The HDR system provided a feedback signal to the tracking controller for closed-loop antenna tracking using the 20-GHz telemetry beacons. The bandwidth of the receive system allowed access to the satellite beacon signal in the equipment trailer. A system was developed inhouse to convert the received signal to the required 0- to 10-V_{dc} input required by the controller. Due to the lack of test equipment available onsite, a spectrum analyzer was used as a beacon receiver to monitor the beacon signal strength. Having the spectrum analyzer onsite provided needed test equipment to troubleshoot anomalies and conduct link characterization measurements. The spectrum analyzer signal (beacon strength) was converted to an analog output for the tracking controller by a computer and data acquisition card.

Like the VSAT and USAT mounts, the HDR antenna-tracking mount was also designed and fabricated inhouse. The HDR antenna was custom made by Prodelin Corporation and consisted of a four-petal, 23.5°-offset, 3.4-m Ka-band dish bolted to a fixed mount frame. Figure 11 shows the antenna after the in-house modifications were complete for inclined

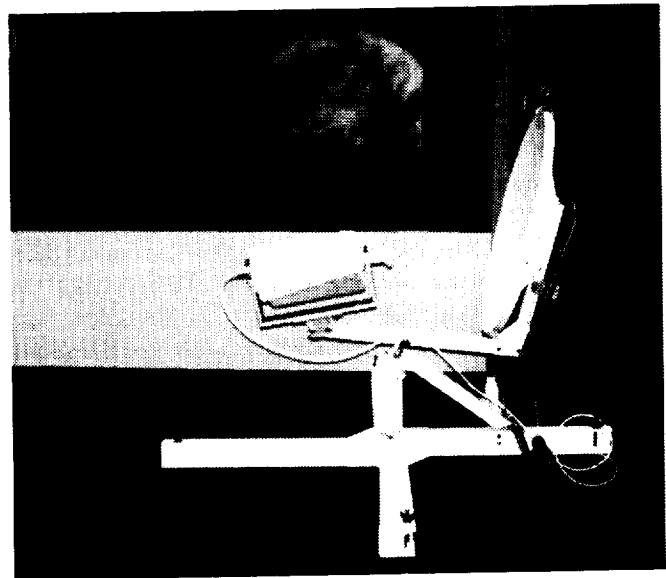


Figure 10 USAT inclined orbit mount.

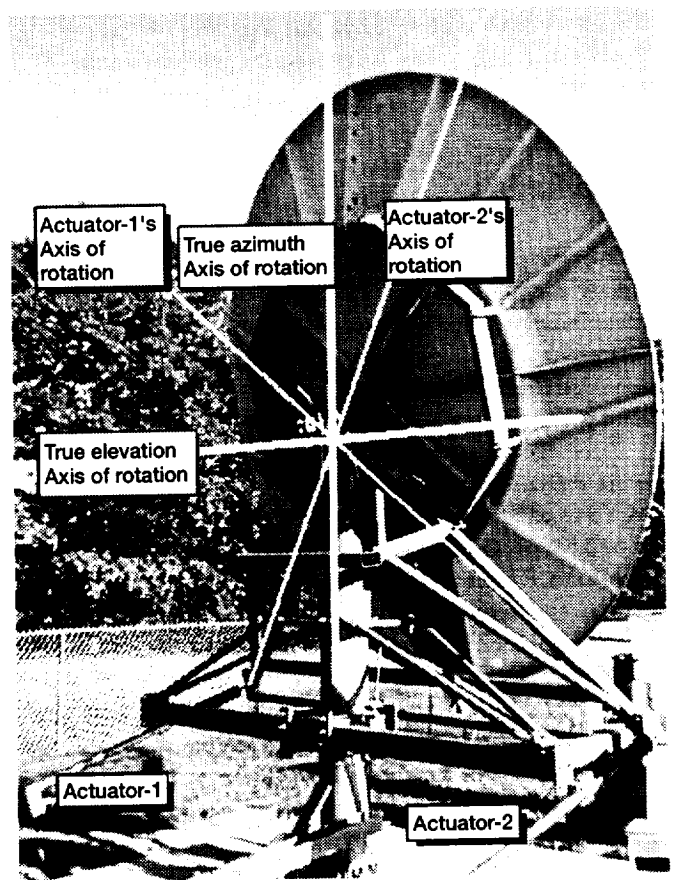


Figure 11 HDR inclined orbit mount.

orbit operations. Although the design worked well for HDR tracking, the initial pointing of the antenna was more difficult compared to traditional mounts because the axis-of-rotation (highlighted in fig. 11) of each actuator was offset 45° from

traditional mounts. The offset design partially balanced the weight of the antenna allowing simpler modifications and smaller actuators.

The NGS and LET step trackers provided very accurate tracking of the spacecraft and were used to provide spacecraft location inputs to ephemeris calculations. As discussed in reference 7, fade effects are known to affect step tracker pointing accuracy, particularly when the fade level fluctuates during the execution of the tracking algorithm. These effects were observed in both the NGS and LET systems. Multiple features, including memory track, fade level, and fade rate thresholds are available in the trackers to set algorithm parameters so as to mitigate these effects. Early in the program some operations impact occurred due to antenna pointing effects. However, parameters were adjusted to reduce the occurrence of these effects significantly. There are several factors to be considered. Additional experimentation would be desirable but is limited to times of appropriate weather conditions and by the need to minimize impact to gateway station operation. The alternative technology of monopulse tracking is less susceptible to propagation effects, but is more expensive to implement. System designers faced with cost-benefits tradeoffs can note that step tracker technology has been used successfully in the ACTS program.

Conclusion

Over the past 7 years the Advanced Communications Technology Satellite (ACTS) Program has successfully demonstrated advanced applications and services using ACTS through experiments and demonstrations. Key to the experiments and demonstrations were the deployment and operations of the Ka-band ground stations.

Three classes of transportable earth stations ranging in antenna diameter size from 0.35 to 3.4 m provided access to ACTS to conduct applications using data rates from 4.8 Kbps to 622 Mbps. Ground-station operations provided many lessons learned over the years in technology development, integration, and maintenance. Two gateway earth stations located at GRC provided (a) tracking, telemetry and control of ACTS, (b) the reference station of the BBP Time Division Multiple Access (TDMA) network and MSM satellite-switched TDMA network, and (c) conducted high-data-rate interoperability experiments and link characterization experiments. The Ka-band technologies described in this report were applied in various ways to the field and gateway earth stations.

This report summarizes the Ka-band technologies, station hardware integration and configuration, and lessons learned throughout the program. Included is a discussion of the ACTS inclined orbit operations and required modifications to the

ground stations. The ground station's inclined orbit design and performance present various alternatives to implementing closed-loop-tracking systems.

References

- ¹Coney, T.A.: Advanced Communications Technology Satellite (ACTS) Baseband Processor Mode (BBP) System Performance. NASA Technical Paper, NASA Lewis Research Center, Cleveland, OH, 1996.
- ²Lee, Kerry D.: Design and Development of a Baseband Processor for the Advanced Communications Technology Satellite. Proceedings of the Advanced Communication Technology Satellite Results Conference, NASA CP-10183, 1996.
- ³May, Brian D.; Kerczewski, Robert J.; and Svoboda, James S.: Anomalous TWTA Output Power Spikes and Their Effect on a Digital Satellite Communications System. NASA TM-105875, 1992.
- ⁴Fijikawa, Gene; and Svoboda, James S.: Test Results of a 20 GHz, Low Noise Downconverter for USAT Applications. NASA TM-106892, 1995.
- ⁵Reinhart, Richard C.: System Design and Applications of the Ultra Small Aperture Terminal with the Advanced Communications Technology Satellite. NASA TM-107536, 1997.
- ⁶Acosta, Roberto J.: Special Effects: Antenna Wetting, Short Distance Diversity, and Depolarization. Paper presented at the Sixth Ka-Band Utilization Conference, NASA Glenn Research Center, Cleveland, OH, June 2000.
- ⁷Struharik, S.J.; and Meadows, D.N.: The ACTS Master Ground Station Design and Performance. Proceedings of the Advanced Communications Technology Satellite Results Conference, NASA CP-10183, 1996.
- ⁸Acosta, R.J.; and Johnson, S.: Six Years of ACTS Technology Verification Experiment Program Results. Paper presented at the Fifth Ka-Band Utilization Conference (Taormina, Italy), Oct. 1999.
- ⁹Reinhart, Richard C., et al.: Modem Characterization Through a Wideband, Hard-Limited Ka-Band Satellite Channel. NASA/TM-1999-209454, 1999.
- ¹⁰Kerczewski, Robert K., et al.: CW Interference Effects on High Data Rate Transmission Through the ACTS Wideband Channel. NASA TM-107156 (AIAA Paper 96-1104), 1996.

¹¹Acosta, Roberto J.: Advanced Communication Technology Satellite (ACTS) Multibeam Antenna Analysis and On-Orbit Performance. Presented at the Second Ka-Band Utilization Conference (Florence, Italy), Sept. 1996.

¹²Hoder, Douglas; and Bergamo, Marcos: Gigabit Satellite Network for NASA's Advanced Communication Technology Satellite (ACTS). *Int. J. Satell. Commun.*, vol. 14, no. 3, 1996, pp. 161–173.

¹³Kearney, Brian; and Hoder, Douglas: High Data-Rate Ground Station for the Acts Gigabit Satellite Network (GSN). *Proceedings of the Advanced Communication Technology Satellite Results Conference, Part 1*, NASA Lewis Research Center, Cleveland, OH, 1996.

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13. ABSTRACT (Maximum 200 words) The Advanced Communications Technology Satellite (ACTS) Project invested heavily in prototype Ka-band satellite ground terminals to conduct an experiments program with ACTS. The ACTS experiments program proposed to validate Ka-band satellite and ground-station technology, demonstrate future telecommunication services, demonstrate commercial viability and market acceptability of these new services, evaluate system networking and processing technology, and characterize Ka-band propagation effects, including development of techniques to mitigate signal fading. This paper will present a summary of the fixed ground terminals developed by the NASA Glenn Research Center and its industry partners, emphasizing the technology and performance of the terminals and the lessons learned throughout their 6-year operation, including the inclined orbit phase-of-operations. The fixed ground stations used for experiments by government, academic, and commercial entities used reflector-based offset-fed antenna systems with antennas ranging in size from 0.35 to 3.4 m in diameter. Gateway earth stations included two systems referred to as the NASA Ground Station (NGS) and the Link Evaluation Terminal (LET).				
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